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REDUNDANCIES IN HUMAN BIOMECHANICS AND THEIR APPLICATION
IN ASSESSING MILITARY MAN-TASK DISABILITY PERFORMANCE
RESULTING FROM BALLISTIC AGENTS

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ABSTRACT. Nervous system redundancies have a counterpart in human biomechanics which are evident when analyzing man-task performance using simulations of functional disabilities. These multiple choice pathways available for task accomplishment could explain some of the surprisingly small drops in performance in the presence of otherwise significant tissue trauma especially in cases of highly motivated soldiers. Such findings are thought to be useful in a bioengineering approach for optimizing man-machine or man-task relationships and deriving technical rules for the design of body armor and protective clothing for minimizing personal injury from ballistic agents.

INTRODUCTION. This is a discussion concerning a problem which associates engineering and medicine in a military context. As such it is a cross-application of exact and inexact sciences. With the advent of more intensive interest in mathematical applications to biological problems and the maturation of systems analysis, one now has more formidable tools with which to attack such problems. However, this discussion is restricted to an identification of the natural conditions allowing for multiple choice pathways in task accomplishment. No mathematical model is proposed.

Engineering and mathematical applications to systems behavior, particularly "living-systems", have brought about many new ideas regarding complex problem analysis. An effect of this has been and is, increasingly, that of providing us with more understanding of the nature of these systems. This encourages us to go back to our natural systems for re-examination but with more enlightenment on what we are really looking for.

This morning attention is directed to the response of complex living systems, specifically, humans, under a very large spectrum of traumatic or wounded states. Such interactions are of interest in a setting of military stress situations. Furthermore, it is important to correlate these responses with performance associated with defined tasks (or military occupational specialties) as they appear in the various tactical roles.

In our first approximations, we assume the presence of sufficiently high motivation such that if, despite the presence of trauma, a human biomechanical capability to perform in any fashion exists, it will be used. Consideration today will be restricted to qualitative structure-function relationships and useful methods of analysis. There is significant starting data relating to gross mechanisms for uninjured human function in terms of anatomical and physiological knowledge. One useful approach to this kind of problem is the use of simulation procedures and gaming. This could give us some idea of the value of a loss of function regardless of cause. Obviously wounds cannot be directly simulated, but many endpoint effects in terms of functional disabilities can be. Finally, another essential is the ability to study man-task interactions as they relate to accepted performance levels. In this respect industrial engineers, ergonomists, and applied experimental psychologists are evolving much useful information.

DISCUSSION. Ballistic agents directed at potential enemy soldiers are assessed in terms of the incapacitating effects which they bring about. A wound per se may have little meaning in a military stress situation unless it is matched against task requirements. Incapacitation is defined in this frame of reference as the "diminished capability to perform a defined task." Specifically, a wounded enemy soldier may have an otherwise serious wound in an upper limb, but should his task (military occupational specialty) require the use of only one limb to handle his weapon or machine for counter use during the stress engagement, and thereby effectively incapacitate his enemy (us), then the incapacitating effect of our ballistic agent is not great. It may not even be significant. Of course, the converse may be true. A small but deeply penetrating wound may be very incapacitating. An example of the latter could be one in which a soldier is required to have extremely fine motor coordination in both limbs simultaneously in order to perform the task adequately. In this case, quite a large variety of small penetrating wounds at various anatomical locations could be cited in which motor (muscle) control would be lost resulting in either an inability to control fine movement or an inability to manipulate the entire limb into position for accomplishing the fine movement. The point, of course, in this definition of incapacitation is the fact that an evaluation concerns, not man alone, but man coupled to his assigned tasks in prescribed environments.

As physicians we think in terms of pathological mechanisms pertaining to injury. Such understanding is predicated, in turn, on knowledge

from the basic medical sciences. Functional disabilities ascribable to any spectrum of injuries are assumed to be variable and time dependent. Functional deficits are related in this human system analysis to the final common motor pathway which is a clinical way of referring to one's reactive muscle mechanics. This applied concept is useful inasmuch as the interlock existing between man and his external physical mission or mechanical work is to be accomplished is one of dynamic character. At times this interlocking dynamics is characterized by numerous physical actions while at other times, such actions are numerically minimal but the physiological requirements are intense. In any event, it is obvious that in studying human actions we must deal with a complex integration of both physical and physiological factors.

As engineers we express work in terms of force times distance. Physiologically we have often considered work on the part of a living system as an expenditure of metabolic energy. In this sense we are, of course, in error in our definition of work. We need to differentiate between metabolic energy utilized for life support or maintenance of homeostasis and that metabolic energy available and employed to accomplish "useful" external work. In engineering we sometimes use the expression "useful work" when discussing thermal efficiency of a machine. For example, the thermal efficiency of a locomotive may be 8 per cent, meaning that 8 per cent of the available energy is converted to so many foot-pounds of output and the remainder to heat. However, in handling the combination of inanimate and animate (man and weapon), some practical criteria for NORMAL man-task behavior are needed against which one can assess performance for incapacitated states.

In our first approximations, it appears practical to use a qualitative form of biomechanics providing we can correlate this satisfactorily with appropriate performance levels as derived from experimental analysis. Anthropometrical, physiological, and psychological variations in the human are, of course, an integral part of any appraisal of human function and behavior in the final analysis. Hopefully one looks forward to mathematical expressions for causal relations that are valid and reliable.

Man is endowed with considerable versatility. The use of this versatility is influenced by the mind (brain), body, and environment. The need to relate wound tract pathology with the internal biomechanics of body actions is apparent. However, we also find it useful to study overall functional behavior while in action in order to get impressions of the

sequential dynamics that differentiate one kind of task from another. These applied human mechanics can be studied in terms of their mechanistic factors . . . i. e., bone-muscle function. In the long run our model must include input factors such as sensing and/or kinesthetic items as well as kinematics, time-varying factors such as endurance and fatigue, and system alterations due to environment in this total biological-task-environmental stress system problem.

The biophysics and pathological dynamics of wounding are matters of great importance but beyond our scope this morning. We will attempt here to explore the problem in reverse. We may begin with certain functional (motor) deficits which could conceivably be derived from one or more wounds. In the future we expect to assess other factors in the human circuitry such as loss of sensory function, kinesthetic changes, and trauma to the body subsystems such as the nervous system, cardiovascular system, and respiratory system. We hope to be able to draw from others doing human research in the life sciences and biotechnology. As mentioned, we will try to relate traumatic effects to that final common motor pathway. By simulating motor deficits we are, in effect, working backwards. The more general motor deficits are not difficult to simulate and as such enable us to make at least first approximations of man-task (soldier-weapon or soldier-task) performance behavior as this occurs in simulated tactical role exercises. Incidentally, it is felt that this approach will allow us to do as Professor Pearson outlined yesterday weld together the important elements including mathematical and war and computer games on the one hand and laboratory experiments, range trials, and Army exercises on the other.

Our view of a human-task model includes the following factors:

1. The Human or Living Machine
2. Tasks
3. Interactions of the Living Machine and Task
Accomplishment
4. Environment (not discussed in this paper)

The Human or Living Machine.

In our present work, the human body is being considered as a living machine endowed with a natural structural system capable of serving its internal biological needs while performing external tasks. Many sources

Design of Experiments

are available for descriptions of human mechanics. The Hall of Biology of Man of the American Museum of Natural History is one of these. Anatomists, particularly J. C. Grant (A Method of Anatomy) and G. B. Duchenne (The Physiology of Motion, more recently translated by E. B. Kaplan of Columbia University), offer very detailed work along these lines. Your attention may have been attracted recently to the present series of articles in LIFE Magazine which discusses some of the biomechanics of the human body.

While many people have not thought about human function in terms of mechanics, they are not particularly surprised when human activity is conservatively compared with mechanical devices. It is also not difficult to see that some overlap or redundancy must exist in a system in which the parts are so intricately intertwined as in the human.

Studies of normal (non-injured) human subjects performing given tasks show that different people use different methods in performing them. In addition, these methods are modified as subjects become more accustomed to the tasks. We say that workers become conditioned or skilled in their tasks. Handicapped workers are often forced to use even radically different methods. In the few simulated incapacitation studies that we have made, we have found a considerable variety of methods employed by our limited number of subjects. In a real sense, then, we can consider this multiplicity of methods in terms of biomechanical redundancies. As a matter of fact, one can often explain the adaptation or describe the compensatory pathway chosen on the part of a disabled individual when a more natural one is not available for performing a given task.

Tasks.

Turning briefly to the applied or task side of the picture, i. e., the nature of the things that impose motor output requirements on the human machine, we find an almost endless array of situations. Knobs have to be grasped, turned, and released; levers (such as rifle trigger, bolt, etc.) have to be pulled and pushed; things have to be grasped, raised, lowered and released; buttons have to be pushed, tools have to be handled, vehicles guided, etc. All such physical tasks may be arbitrarily viewed as being accomplished by composites of elementary actions performed by the human (machine).

Interactions of the Living Machine and Physical Tasks.

Viewing the human machine in action shows a link-linkage system including its affixed but integrated motors which raise and lower limbs (for walking, lifting objects, etc.), raise, lower, turn, and tilt the head, etc. Identification of these muscle-motor systems, their sequence(s), and associated force factors can be studied extensively. Muscle and joint functions are quite well known. Their motion and force vectors can be studied. The kinematic processes activated by the human motors can be at least approximated by various methods and are very informative from both qualitative and quantitative points of view. Data are being generated in many of the associated sciences involved in the type of cross-application presented here, and the ways and means are evolving rapidly for handling such massive bits and pieces of acquired information. The need for the systems analysis has already been mentioned. Information handling, cybernetic modeling using acceptable analogs, computer technology, statistical and adaptive control techniques are included in the knowledge sources useful in understanding complex system behavior.

Today I would like to call attention to a very crude experiment which indicates the multiplicity of motor pathways available to the human in performing given tasks. Variations in weapon design, man-task functional modes, objective definitions, parameters and boundary conditions have not been specified from a systems viewpoint. We have used very simple immobilization techniques for inhibiting certain motor functions in order to enforce and observe the use of alternative motor pathways. This experimental exercise has to do with rifle firing and reloading. The target is about 2 feet by 2 feet at a distance of approximately 40 yards on a flat terrain. One of the first questions of interest to us was, "Can one perform under functional disability conditions, rather than how well"? However, as you will see from the film, we get cues as to how well one does and can perform.

In order to be a little more inclusive, the rifle experiment was run using two different weapons, namely, the U. S. M-14 and the Russian AK both of which are standard items. We will not speculate on weapon differences as such, but we will mention a few things about a man-rifle relationship with and without functional losses. You will observe in the film that a soldier can fire his weapon quite effectively in all firing positions without either upper limb. Pistol grips and monopods seem to be quite helpful to a soldier so disabled. Now let us view the film.

A MAN-TASK DISABILITY EXERCISE: RIFLE FIRING. Time will allow for only a few general remarks. I would like to say that the more one reviews and studies motion pictures of man-task behavior the more one can comprehend the biomechanics taking place in such exercises. The anatomist may be the first to observe the variations in anatomical mechanics; the statistician may quickly detect probabilities in terms of cause and effect relationships; the abstract mathematician may see early cues for a stochastic model; the mechanical engineer may be the first to note the vectorial mechanics in 3-dimensional space; the physiologist may immediately observe the abrupt discontinuities in the human functional activities and feel more sensitive about the corresponding metabolic requirements involved; etc.

At this time, we have no valid statistical data. In our very crude investigation, we have observed with caution, of course, the following:

1. Partial losses up to and including either total limb did not prevent the subjects from firing and maneuvering.
2. Target scores did not decrease much below the 65% - 75% accuracy range even for the most severe simulated disability that we employed . . . the inability to use the trigger arm.
3. Firing rates and reload times were only a few seconds longer in the absence of a total upper limb.
4. The motions exhibited by the subjects are somewhat influenced by size, shape, and weight characteristics of the weapons. However, required body positions . . . standing, prone, etc. . . . naturally influence the biomechanical adjustments which must take place.

MOTION STUDY OF HUMAN ACTION. Since human work is accomplished by means of body actions, the study of body movements has evolved as one of the principal approaches to the problem of finding more effective ways of performing tasks. From such empirical studies, rules have been developed which are available for more effective application in planning and designing tasks, machines, and weapons. Skillful application of these principles diminishes fatigue. It is interesting but, perhaps, not surprising that the methodology proposed for the study of incapacitation i. e., functional deficit simulation, is useful in studying normal man-task phenomena.

In recent years, physicians, applied experimental psychologists, physiologists, and engineers have been studying performance factors and have developed considerable empirical data especially in regard to environmental perception and functional response. Others giving much thought to human anatomical function include (in addition to anatomists) orthopedists, physical therapists, and designers of prostheses. Functional anthropologists, physicists and advanced systems engineers are also becoming essential participants in this area of activity. However, we have not fully recognized the capabilities of these professions in cross-discipline or cross-professional applications. A sizeable effort has been directed in more recent years, to a so-called ergonomic approach to man-task analysis especially in Europe. This approach places more emphasis on the integration of anatomy, psychology and physiology as well as economics for solving problems in human performance.

The Gilbreths, pioneers in the development of human motion principles, devised a list of 17 so-called "elements" or "therbligs" as they have been called. Such elements have been considered as basic units of motion and apply for the most part to the upper limb functions. They include such terms as "transport empty" meaning moving the hand from one position at a work place to another in that vicinity; "transport loaded" meaning the same thing except that the hand is now carrying an object in which case the characteristics of the object are specified; "grasp" meaning a securing of an item either by a pinch-grasp performed by the fingers or a palmar-grasp as performed by enclosing the hand about the item; "hold" meaning that the hand in question is maintaining an object in a fixed position while, perhaps, the opposite hand is doing something to the object as may occur in an assembly operation; etc. In each case, the elements are timed. Therbligs are usually measured to one-thousandth of a minute. Stopwatch time and motion study engineers usually measure their elements in terms of one-hundredth of a minute. Instead of using therbligs, they use descriptive terms which are more general, such as "pick up hammer", "tap dowel to flush position", "place hammer aside", "place assembly in tote box", and "measure outside diameter with micrometer". As long as the motions are defined and measured consistently, they are useful in the analysis and the synthesis of operations.

Very quickly I would like to show you the motion study and analysis technique for a given operation which is described on the following slides (figures). Our slides show several motion study charts based on a hypothetical exercise. In slide 1 (Figure 1) we show a "Right-hand: Left-hand Chart" and for simplicity only the actions of the hands are described.

MOTION ANALYSIS - STEP I

OPERATION: BRING RIFLE TO BEAR ON TARGET FROM THE *PORT ARMS* POSITION TO THE *SHOULDER AIM* POSITION, FIRE SIX ROUNDS, AND RETURN RIFLE TO THE *PORT ARMS* POSITION.

<u>RIGHT HAND</u>	<u>LEFT HAND</u>
1. <i>HAND ASSISTS IN BRINGING THE RIFLE (REAR STOCK) TO RIGHT SHOULDER WHILE INDEX FINGER IS LOOSELY POSITIONED ON THE TRIGGER. THE HAND MAINTAINS A MODERATELY FIRM GRIP ON THE STOCK.</i>	1. <i>HAND ASSISTS IN BRINGING RIFLE (FRONT STOCK) TO THE SHOULDER LEVEL, WITH PALM AND FINGERS MAINTAINING A FIRM SUPPORT AND GRASP.</i>
2. <i>THE REAR STOCK IS POSITIONED AGAINST THE FRONT OF THE SHOULDER; THE HAND INCREASES ITS GRIP ON THE STOCK EXCEPT FOR THE INDEX FINGER WHICH MAINTAINS AN ESSENTIALLY NEUTRAL POSITION.</i>	2. <i>THE FRONT STOCK IS POSITIONED IN CONJUNCTION WITH THE REAR STOCK AND THE HAND TAKES ON A MODERATELY SEVERE SUPPORT FUNCTION.</i>
3. <i>WHILE THE HAND (AND FINGERS, EXCEPT THE INDEX FINGER) MAINTAINS A FIRM GRIP ON THE REAR STOCK, THE INDEX FINGER PURES AGAINST THE TRIGGER, INCREASING THE PRESSURE UNTIL IT TRIPS THE FIRING PIN.</i>	3. <i>HAND SUPPORTS THE FRONT STOCK.</i>
4. <i>IMMEDIATELY AFTER ABSORPTION OF THE RECOIL, THE INDEX FINGER IS SHIFTED (MEETING NO RESISTANCE) TO THE ORIGINAL POSITION OF THE NEXT ROUND.</i>	4. <i>HAND SUPPORTS THE FRONT STOCK.</i>
5. <i>SAME AS 3.</i>	5. <i>HAND SUPPORTS THE FRONT STOCK.</i>
6. <i>SAME AS 4.</i>	6. <i>HAND SUPPORTS THE FRONT STOCK.</i>
7. <i>SAME AS 3.</i>	7. <i>HAND SUPPORTS THE FRONT STOCK.</i>
8. <i>SAME AS 4.</i>	8. <i>HAND SUPPORTS THE FRONT STOCK.</i>
9. <i>SAME AS 3.</i>	9. <i>HAND SUPPORTS THE FRONT STOCK.</i>
10. <i>SAME AS 4.</i>	10. <i>HAND SUPPORTS THE FRONT STOCK.</i>
11. <i>SAME AS 3.</i>	11. <i>HAND SUPPORTS THE FRONT STOCK.</i>
12. <i>SAME AS 4.</i>	12. <i>HAND SUPPORTS THE FRONT STOCK.</i>
13. <i>SAME AS 3.</i>	13. <i>HAND SUPPORTS THE FRONT STOCK.</i>
14. <i>SAME AS 4.</i>	14. <i>HAND SUPPORTS THE FRONT STOCK.</i>
15. <i>OPPOSITE OF 1.</i>	15. <i>OPPOSITE OF 1.</i>

FIGURE 1

You observe that the wording in this first slide is in lay language and is lengthy, but this was done purposely for our presentation. The motions of each hand are described singly, and then listed synchronously, one beside the other. You will see more clearly in the next slide the relationship of the activities of each hand. However, this first slide does show how motions are described in terms of elements and a method for analyzing them.

In Slide 2 (Figure 2) you see a condensation in the language as compared to Slide 1. This terminology is often employed by motion analysts. Note how quickly you can get a visual time-history of the events on the part of each hand. In order to emphasize the more important factors in such an operation, one usually includes a clear descriptive summary showing numerical relationships between active and inactive motions.

This same operation cycle has been made a little more sophisticated in Slide 3 (Figure 3) by adding a graphical representation for the various kinds of elements. One purpose of this format is to emphasize the idle or inactive elements. I should point out that ordinarily these graphical representations are in terms of time per element giving a quantitative as well as a qualitative measure. Our example here is hypothetical and admittedly would be more effective if a full motion-time study were made. However, the purpose is to point out a methodology useful in studies relating body mechanics to machine and/or task characteristics.

By applying this technique to human tasks and translating such observations into anatomical mechanics, one may be able to specify in more detailed fashion the various biomechanical pathways employed by humans for given functional disabilities. We all know of unusual accomplishments on the part of some handicapped workers. The same is true for some accident victims immediately following trauma. Certainly the time parameter and undoubtedly a host of others are important, such as environmental conditions, task nature, human motivation, etc., and should be specified in modeling man-task behavior under conditions of disability. In this way, redundant bio mechanical networks available to the human may be weighted and probabilistic methods applied. It is, of course assumed to be necessary to have a definition for normal performance for any given task as a baseline.

MOTION ANALYSIS - STEP I

OPERATION: BRING RIFLE TO BEAR ON TARGET FROM THE PORT ARMS POSITION TO THE SHOULDER AIM POSITION, FIRE SIX ROUNDS, AND RETURN RIFLE TO THE PORT ARMS POSITION.

<u>RIGHT HAND</u>	<u>LEFT HAND</u>
1. TRANSPORT LOADED	1. TRANSPORT LOADED
2. POSITION	2. POSITION
3. PULL LOADED (INDEX FINGER) & HOLD	3. SUPPORT & HOLD
4. PUSH EMPTY (INDEX FINGER) & HOLD	4. SUPPORT & HOLD
5. PULL LOADED (INDEX FINGER) & HOLD	5. SUPPORT & HOLD
6. PUSH EMPTY (INDEX FINGER) & HOLD	6. SUPPORT & HOLD
7. PULL LOADED (INDEX FINGER) & HOLD	7. SUPPORT & HOLD
8. PUSH EMPTY (INDEX FINGER) & HOLD	8. SUPPORT & HOLD
9. PULL LOADED (INDEX FINGER) & HOLD	9. SUPPORT & HOLD
10. PUSH EMPTY (INDEX FINGER) & HOLD	10. SUPPORT & HOLD
11. PULL LOADED (INDEX FINGER) & HOLD	11. SUPPORT & HOLD
12. PUSH EMPTY (INDEX FINGER) & HOLD	12. SUPPORT & HOLD
13. PULL LOADED (INDEX FINGER) & HOLD	13. SUPPORT & HOLD
14. PUSH EMPTY (INDEX FINGER) & HOLD	14. SUPPORT & HOLD
15. TRANSPORT LOADED	15. TRANSPORT LOADED

SUMMARY

	TOTAL NO. OF ELEMENTS	NO. OF ACTION ELEMENTS	NO. OF PASSIVE SUPPORT ELEMENTS
RIGHT HAND	15	15 (100%)	0 (0%)
LEFT HAND	15	3 (20%)	12 (80%)

FIGURE 2

MAN-TASK CHART

OPERATION: BRING RIFLE TO BEAR ON TARGET FROM THE PORT ARMS POSITION TO THE SHOULDER AIM POSITION, FIRE SIX ROUNDS, AND RETURN RIFLE TO THE PORT ARMS POSITION.

<u>RIGHT HAND</u>	<u>LEFT HAND</u>	<u>RIFLE</u>
TRANSPORT LOADED POSITION	TRANSPORT LOADED POSITION	IDLE
PULL LOADED & HOLD	SUPPORT & HOLD	IDLE
PUSH EMPTY & HOLD	SUPPORT & HOLD	INSTANT OF FIRE
PULL LOADED & HOLD	SUPPORT & HOLD	IDLE
PUSH EMPTY & HOLD	SUPPORT & HOLD	INSTANT OF FIRE
PULL LOADED & HOLD	SUPPORT & HOLD	IDLE
PUSH EMPTY & HOLD	SUPPORT & HOLD	INSTANT OF FIRE
PULL LOADED & HOLD	SUPPORT & HOLD	IDLE
PUSH EMPTY & HOLD	SUPPORT & HOLD	INSTANT OF FIRE
PULL LOADED & HOLD	SUPPORT & HOLD	IDLE
PUSH EMPTY & HOLD	SUPPORT & HOLD	INSTANT OF FIRE
PULL LOADED & HOLD	SUPPORT & HOLD	IDLE
PUSH EMPTY & HOLD	SUPPORT & HOLD	INSTANT OF FIRE
TRANSPORT LOADED	TRANSPORT LOADED	IDLE

SUMMARY

	TOTAL NO. OF ELEMENTS	NO. OF ACTION ELEMENTS	NO. OF PASSIVE SUPPORT ELEMENTS	NO. OF IDLE ELEMENTS
RIGHT HAND	15	15 (100%)	0 (0%)	0 (0%)
LEFT HAND	15	3 (20%)	13 (80%)	0 (0%)
RIFLE	15	6 (40%)	0 (0%)	9 (60%)

KEY: VERTICAL HATCHING  = ACTION ELEMENTS
 HORIZONTAL "  = SUPPORT "
 CROSS "  = IDLE "

FIGURE 3

You can see the additional work required to correlate motion mechanics with anatomical causes since we must concurrently consider supporting postural states. The need for unique mathematics is apparent for we are dealing with complex functions. For example, we are interested in the role or contribution of an individual muscle or muscle group in its relationship to an array of essential tasks. This has not been done in the past either by engineers or psychologists to the best of our knowledge for tasks at large.

As stated, it is of primary interest to try and study the relationships that might exist between anatomical structures and their resulting human motion complexes. It becomes obvious that in spite of one or even more than one imposed functional disability, one may perform a defined task satisfactorily. Case studies have been reported where in times of actual injury, humans perform miraculously. Extreme motivation, fear, pain, and a host of other psychological and physiological factors are deeply imbedded. However, if the structure-function pathways did not exist, high motivation alone could not create new physical anatomical entities. Another important spectrum of feasible alternatives derives from the environment not considered in this paper.

In an anatomical review of the upper limb musculo-skeletal system, it is observed that for given muscle dysfunctions, others are often available to assist in the accomplishment of a specified task. Your attention is directed to Table I in which you observe an anatomical matrix of upper limb muscles. The columns are anatomical actions. The rows are the muscles arranged in order from top to bottom to correspond to the proper regions from shoulder to fingers. Notice that in almost all cases, more than one muscle contributes to a given anatomical motion. This is shown by the presence of more than one x in any column.

It is believed that we are getting closer to technical explanations as to why some perform "miraculously" under handicap. It is the motivation that is miraculous, we can do pretty well from the technical or biotechnical point of view.

We are giving serious thought to the development of a functional anatomical-physiological model of man considering all body systems, or subsystems, such as the musculo-skeletal, cardiovascular, nervous, respiratory, gastrointestinal, and genito-urinary, using what physiological feedbacks we know about and can use. Ordinarily we would avoid such

complexity, but you must remember that our analysis actually begins with wound tract pathology or tissue trauma assignable to given fragment physics. A task need not suffer if its imposed demands are not beyond certain limits. Table I shows the structure-function relationships for the human upper limb. Functionally, redundancies are present. This is indicated as mentioned in Table I by examining anatomical functions performed by more than one muscle. In order to be more correct the x's should be of variable size to indicate in a more quantitative sense, weighted contributions on the part of the respective muscles. The point is that redundancies in terms of anatomical capability to perform exists to accomplish external actions. They exist in a given anatomical region. They exist also because of anatomical duality since many tasks are not fully demanding in terms of both limbs simultaneously. Postural changes may compensate satisfactorily for such losses.

RELIABILITY OF SYSTEMS. The reliability of a system's performance may be related to the objective which the system is expected to attain. Since we are concerned with the complex living-system coupled to inanimate components, nature's solutions to reliability phenomena are of special interest. This is especially true if the objective function of a given ballistic fragment is to maximize the disruption of this living-performing arrangement. At the biological-cell level the answer to unreliability is the presence of many more cells than are required, most of which are in parallel linkages. According to W. S. McCulloch, Von Foerster expresses the view that whatever else it (an ordered 'living' system) contributes, a redundancy of structure is fundamental.*,** McCulloch also states . . . "that which is redundant is, to the extent that it is redundant, stable."**

Such phenomena, including information, channels, and structure are important if additional insight is to be attained concerning explanations for the adaptation and compensation powers so often demonstrated by human body behavior.

* "On Self-Organizing Systems and Their Environments," by H. Von Foerster. From "Self-Organizing Systems Proceedings of an Interdisciplinary Conference." Pergamon Press. 1960.

** "The Reliability of Biological Systems," by W. S. McCulloch, same publication.

Reliability can be defined statistically as the probability "P" that an element or a system will perform satisfactorily for a given period of time. Unreliability is the probability of a failure during a specified time and is given as " q " = $1 - P$. Here independence assumes that the failure of one element does not affect the probability of failure of any other element. Trauma from various causes has not yet been studied in this sense, but it is being proposed. However, the lack of knowledge of complex biological system behavior would seem to favor the application of stochastic processes at the present time.

If redundancies exist in human biomechanics as well as for the many supporting subsystems, the act of purposely inhibiting any single channel, even if it were feasible to identify it, may not yield applied information most needed at the present time. Other channels, especially those we are not yet aware of, may take over. However, "groups" of redundant channel inhibition may yield significant responses.

If we study task requirements in terms of biomechanical redundancies, we can begin to describe these pathways. It is well known that no task requires all available channels. Hypothetically, then, performance decrement due to a specific channel deficit may not be significant. Our introductory observations regarding given functional losses for defined tasks show some influence on performance behavior. We are probably dealing in some measure with numerical discontinuities and/or non-linear systems.

But what are the boundary conditions? How will these vary from task to task? How much subsystem understanding is required or when can it simply be "blackboxed"? We feel, as others do, that in complex systems in which there is a problem to be solved, it makes sense to speak of the quality of a solution. The method of solution is determined to a large extent by the problem objective. Herein may lie the reason for some of the differences obtained when many views are taken of the same problem. The approach may be identical but inputs may be biased in various ways. Inputs and criteria obviously influence output numbers.

It is interesting to note that research programs in the life sciences are increasingly accentuating the need for increased knowledge concerning fundamental processes, principles, and mechanisms found in biological systems. For the present, we must formulate and use what basic homeostatic mechanisms known by which body processes are regulated. Studies are being made of adaptive and regulatory processes; neural network theory; reflexes and other feedback systems; random redundant processes;

sensing and transducer mechanisms; the specificity of sensory and motor phenomena and other such functions. It has only been in recent years that interest in the study of physical and mathematical principles relating to control systems has become intensified.

Two general approaches to incapacitation assessment are of immediate interest to us, namely, (1) the medical and biophysical aspects of pathological dynamics for certain fragment physics, and, (2) the probable performance alterations for specified tasks due to the traumatic effects of such traumata.

SUMMARY. In summing, it is believed that the following ideas are important:

1. Humans possess a general-purpose type of anatomical structure-function arrangement. Overlap and redundance, indicated by the fact that more than one muscle contributes to the same anatomical function and the presence of duality particularly in the upper and lower limbs, are factors contributing to the nature of this capability. This same idea may be carried down to the cellular level for a single muscle inasmuch as muscle cells exist in a large number of subsets many of which are in parallel. Finally, we might add that even a single living cell may have different capacities depending on many physiological factors including conditioning.
2. In this context it is felt that the load or demand on the general-purpose human is a significant function of task requirements. Quality of performance, imposed physical forces, variable time durations, environmental factors, and motion behavior in 3-dimensional space are items that may vary radically from one task to another.
3. In assessing disability performance a definition of non-disability performance is essential. We recognize the need for unique combinations of talents in this interdisciplinary problem area.
4. A large amount of experimental information concerning man-task dynamics can be generated for specified tasks using conventional work measurement techniques in conjunction with physiological instrumentation and control system knowledge now available.

Appendix

UPPER LIMB MUSCLE CODE

Code Muscle Name

Shoulder:

A₁ Trapezius
A₂ Serratus anterior
A₃ Subclavius
A₄ Pectoralis minor
A₅ Pectoralis major
A₆ Subscapularis
A₇ Supraspinatus
A₈ Infraspinatus
A₉ Teres minor
A₁₀ Teres major
A₁₁ Biceps brachii
A₁₂ Coracobrachialis
A₁₃ Triceps brachii
A₁₄ Deltoid

Arm:

A₁₁ Biceps brachii
A₁₃ Triceps brachii
A₁₂ Coracobrachialis
B₁ Brachioradialis
B₂ Brachialis
B₃ Anconeus

Forearm:

A₁₁ Biceps brachii
A₁₃ Triceps brachii
B₁ Brachioradialis
B₃ Anconeus
C₁ Supinator
C₂ Pronator quadratus
C₃ Pronator teres
C₄ Flexor carpi radialis
C₅ Extensor carpi radialis longus
C₆ Flexor digitorum sublimis
C₇ Flexor carpi ulnaris
C₈ Extensor carpi radialis brevis
C₉ Extensor carpi ulnaris
C₁₀ Flexor digitorum profundus
C₁₁ Extensor digitorum communis
C₁₂ Palmaris longus
C₁₃ Abductor pollicis longus
C₁₄ Flexor pollicis longus
C₁₅ Extensor indicis proprius
C₁₆ Extensor digiti quinti proprius
C₁₇ Extensor pollicis longus

Code Muscle Name

Hand:

C₆ Flexor digitorum sublimis
C₁₀ Flexor digitorum profundus
C₁₁ Extensor digitorum communis
D₁ Extensor pollicis brevis
C₁₇ Extensor pollicis longus
D₂ Abductor pollicis brevis
C₁₃ Abductor pollicis longus
C₁₄ Flexor pollicis longus
D₃ Flexor pollicis brevis
C₁₅ Extensor indicis proprius
C₁₆ Extensor digiti quinti proprius
D₄ Flexor digiti quinti brevis
D₅ Abductor digiti quinti
D₆ Abductor pollicis
D₇ Palmaris brevis
D₈ Opponens pollicis
D₉ Opponens digiti quinti
D₁₀ Lumbricales
D₁₁ Interossei dorsales
D₁₂ Interossei volares

UPPER LIMB MOTOR FUNCTIONS AND CAUSAL FACTORS

TABLE I
(See Appendix for identification of code)